THE HUMAN COMPONENT OF THE GLOBAL CARBON CYCLE

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The context

Fossil fuels (coal, oil, and natural gas) are used primarily for their concentration of chemical energy, energy that is released as heat when the fuels are burned. Fossil fuels are composed primarily of compounds of hydrogen (H) and carbon (C) and when the fuels are burned the H and C are oxidized to water (H_2O) and carbon dioxide (CO_2) and heat is released. If the H_2O and CO_2 are released to the atmosphere, the H_2O will soon fall out as rain or snow. The CO_2, however, will increase the concentration of CO_2 in the atmosphere and join the active cycling of C that takes place among the atmosphere, biosphere, and hydrosphere. Since humans began taking advantage of fossil-fuel resources for energy, we have been releasing to the atmosphere, over a very short period of time, C that was stored deep in the Earth over millions of years. We have been introducing a large perturbation to the active global cycling of C.

Estimates of fossil-fuel use globally show that there have been significant emissions of CO_2 dating back at least to 1750, and from the United States back at least to 1800. However, this human perturbation of the active C cycle is largely a recent process, with the magnitude of the perturbation growing as population grows and demand for energy grows. Over half of the CO_2 released from fossil-fuel burning globally has occurred since 1980 (Figure 1).

Some CO_2 is also released to the atmosphere during the manufacture of cement. Limestone ($CaCO_3$) is heated to release CO_2 and produce the calcium oxide (CaO) used to manufacture cement. In the United States, cement manufacture now releases less than 1% of the mass of CO_2 released by fossil-fuel combustion. However, cement manufacture is the third largest anthropogenic source of CO_2 (after fossil-fuel use and the clearing and oxidation of forests and soils). The CO_2 emissions from cement manufacture are often included with the accounting of anthropogenic CO_2 emissions from fossil fuels.

This paper addresses the magnitude and pattern of CO_2 emissions from fossil-fuel consumption and cement manufacture. It discusses how much carbon is released and poses the question of who is responsible for this carbon. It also comments briefly on the fate of carbon once released to the atmosphere and on alternatives to letting the carbon accumulate in the atmosphere.

Estimating CO_2 emissions

It is relatively straightforward to estimate the amount of CO_2 released to the atmosphere when fossil fuels are consumed. Because CO_2 is the equilibrium product of oxidizing the C in fossil fuels, we need to know only the amount of fuel burned and its C content (and if some of the fuel is used in ways that do not involve oxidation, e.g. for highway asphalt or to manufacture plastics). We can report either the amount of CO_2 produced or the amount of C in that CO_2, and in this paper we prefer to report the amount of contained C (the amount of CO_2 produced can be gained by multiplying the C content by the ratio of the molecular masses, 44/12). Throughout this paper "tons" are metric tons.

The rate of CO_2 emitted per unit of useful energy released is different for the different fossil fuels and depends on the ratio of H to C in the fuel and on the details of the organic compounds in the fuels. Roughly speaking, the numerical conversion from energy released to C released as CO_2 is about 25 kg C per 10^9 joules for coal, 20 kg C per 10^9 joules for petroleum, and 15 kg C per 10^9 joules for natural gas. Table 1 shows some of the exact coefficients reported by the Intergovernmental Panel on Climate Change (IPCC) for estimating CO_2 emissions.

The uncertainty in estimates of CO_2 emissions will thus depend on the variability in the chemistry of the fuels, the quality of the data or models of fuel consumption, and on uncertainties in the amount of C that is used for non-fuel purposes or is otherwise not burned. For countries like the US; with good data on fuel production, trade, and consumption; the uncertainty in estimates of national emissions of CO_2 is on the order of +/- 5% or less. In fact, the US Environmental Protection Agency (USEPA, 2005) suggests that their estimates of CO_2 emissions from energy use in the US are accurate, at the 95% confidence level, within –1 to +6 %. When national emissions are calculated by consistent methods it is likely that year-to-year changes can be estimated more accurately than would be suggested by the uncertainties of the individual annual values.

The magnitude of national and global CO_2 emissions

Figure 2 shows that from the beginning of the fossil-fuel era (1751 in these graphs) to the end of 2002, there were a cumulative total of 84.4 billion tons of carbon released as CO_2 from fossil-fuel consumption (and cement manufacture) in the United States. The global total was 298 billion tons of carbon so that the United States contribution is about 28.3%. Figure 3 shows the annual total of emissions from the United States and the contributions from the different fossil fuels. For the year 2002, the US contribution was about 22.7% of the global total. The US fraction of the global total has been shrinking with time.

Figure 4 provides our best estimates of the global total of CO_2 emissions for each year from 1750 to 2003 and includes our very recent estimates for 2004 and 2005. The 2004 and 2005 values are preliminary estimates based on energy data published by BP Company and are subject to revision, but they clearly show that emissions are increasing dramatically in the most recent years. The 2005 value is a 28% increase over the 1990 value.

Emissions by state and economic sector

To understand how CO_2 emissions from fossil-fuel use interact in the global and regional cycling of carbon, it is necessary to know the masses of emissions and their spatial and temporal distribution. We now have data sets that describe US emissions by state and by month (e.g., Blasing et al., 2005a and 2005b). To understand the patterns and trends of CO_2 emissions, the driving forces behind those trends, and the opportunities for reducing emissions, it is also useful to examine emissions by economic activity. These kinds of spatial and sectoral data also raise interesting issues abut the responsibility for CO_2 emissions, an issue that I will refer to as "my carbon and your carbon".

Before looking at some details of how energy is used and where CO_2 emissions occur in the United States and in the US economy, however, there are two indices of CO_2 emissions at the national level that provide perspective on the scale and distribution of emissions. These two indices are emissions per capita and emissions per unit of economic activity, the later generally represented by CO_2 per unit of gross domestic product (GDP). Figure 5 shows the 1950 - 2002 record of CO_2 emissions per capita for the 3 countries of North America and, for perspective, includes the same data for the global total. Note that per capita emissions in the United States are largely unchanged since 1970 and that they are roughly 5 times the global average. Similarly, Table 2 shows CO_2 emissions per unit of GDP for the three countries of North America and for the world total. Emissions of CO_2 per unit of GDP have been declining for over 2 decades in the United States (see U.S. DOE, 2005) and are only slightly higher than the global average value.

Emissions per capita and emissions per unit of GDP are, of course, very complex indices and though they provide some insight they say nothing about the details and the distributions within the means. The data on CO_2 per capita for the 50 U.S. states (Figure 6) show that even within the United States values range over a full order of magnitude, differing in complex ways with the structure of the economies and probably with factors like climate, population density, and access to resources (Blasing et al., 2005b; Neumayer, 2004). For example, Figure 6 provides an illustration of the role of the distribution of resources and of trade in energy intensive products. To take an extreme case, we can compare per capita emissions in Wyoming and California. Data from the Energy Information Administration show that per-capita energy use in 2000 differed by a factor of 4 between Wyoming and California, Figure 6 shows that per capita CO_2 emissions differed by a factor of nearly 12. A significant portion of the difference can be explained with data on how and where electricity is generated. In Wyoming, in 2000, 97% of electricity generation was using coal and 71% of the electricity generated was traded out of state. In California, in 2000, 1% of electricity generation was using coal and 23 % of the electricity consumed in California was imported from out of state. Per capita emissions from

Wyoming are very high because most of their electricity is generated with coal and because they generate electricity for other users. In essence, from the perspective of Wyoming, it is your electricity but my CO_2 emissions.

International data also illustrate the problem of subdividing the global system and trying to account for your C and my C. Of the growth in global CO_2 emissions from 1990 to 2005 (see Figure 4), nearly half can be found in China. But Shui and Harris (2006) estimate that 7 to 14% of current CO_2 emissions from China are a result of producing goods for consumption in the United States. Similarly, the Canadian national inventory of greenhouse gas emissions (Environment Canada, 2005) estimates that 6.6% of Canadian emissions are for the production, processing, and transport of natural gas and oil that are exported, mostly to the United States. Saving electricity in Norway likely results in reduced CO_2 emissions in Denmark, because it frees up Norwegian hydropower for export (Sjödin and Grönkvist, 2004). Of course, countries both import and export embodied CO_2 emissions in a great variety of commodities and finished goods. Thus, as countries (and other political subdivisions) rely increasingly on trade to meet their material needs, it is not an easy task to understand what the magnitude of domestic CO_2 emissions really means.

Estimating emissions by sector brings special challenges in defining sectors and assembling the requisite data. Nonetheless, the database of the International Energy Agency allows us a rough idea of how emissions are distributed among major sectors in the United States and how this compares with the other countries of North America (Table 3). The fact that the United States gets 51% of its electricity from coal while Mexico gets 68% from petroleum and natural gas and Canada gets 58% from hydroelectric stations gets superimposed on the differences in the structure of the economies and the varying importance of transport and factors as varied as climate and the mix and efficiency of industrial processes.

The US Department of Energy (2005a) shows similarly that 39% of US CO_2 emissions in 2004 came from generation of electric power with another 33% from transportation. Emissions of CO_2 have dropped from 0.205 kg C/kwh of electric power generation in 1970 to 0.167 kg C/kwh in 2004 as the mix of fossil fuels has evolved and the contribution of nuclear plus renewables has increased (Marland and Pippin, 1990; US Department of Energy, 2005b).

Full carbon accounting or life cycle analysis

The human component of the global carbon cycle has been seen to be interwoven with the global economic system. Changes in the stocks or flows of C in one place or one sector often have impacts on the stocks and flows of C in other places, other economic sectors, and other times. This suggests that strategies to manage CO_2 emissions be examined to see their full implications. Examining the complete life cycle of a product or service can reveal the range of impacts on the global cycling of carbon (and on emissions of other greenhouse gases). Conversion from conventional to no-till agriculture has been analyzed and provides a simple example of the full implications on the carbon cycle when agricultural practice is altered. Conversion from conventional to no-till agriculture has been recognized as a way to increase sequestration of C in agricultural soils and thus to reduce net CO_2 emissions to the atmosphere. This shift in practice also influences the amount of fuel used on the farm, the amount of fertilizer and other inputs to agriculture, and perhaps agricultural productivity. Our initial (Figure 7) analysis suggests that for average practice in the United States the sum of changes in greenhouse gas emissions is in fact greater than the amount of carbon sequestered in soils, but it demonstrates clearly that the affected system is larger than simply the C content of the soil.

Carbon management

When fossil fuels are burned the CO_2 is generally discharged to the atmosphere. Once in the atmosphere the active cycling of C will, over time, distribute this excess C among the atmosphere, the oceans, and the various components of the biosphere. It is possible to exercise some management over these processes by either promoting the removal of CO_2 from the atmosphere or collecting CO_2 at the points of fuel combustion or processing and putting it places where it is not mixed into the atmosphere.

Carbon removed from the atmosphere by photosynthesis can be managed to increase the C storage in forests or soils. Alternatively, the biological material can be harvested and used as a renewable fuel to displace fossil-fuel combustion. A third alternative is to harvest and use biological materials, such as wood, in the place of alternate materials that require more energy for their production and use.

The Intergovernmental Panel on Climate Change (IPCC, 2005) has estimated that there are nearly 8000 large, stationary, industrial sources (63% are large power plants) of concentrated CO_2 with emissions of more than 100,000 tons of CO_2 per year - and hence large enough to contemplate collection and storage of the CO_2. These large sources accounted for 60% of total global CO_2 emissions in 2000. The potential for long-term storage of this C in exhausted oil and gas fields, unminable coal seams, and deep saline aquifers appears to be very large and several demonstration projects are now proceeding worldwide. There is, of course, a cost for this CO_2 collection and storage, and it is estimated that 10% to 40% additional fossil fuel would have to be burned in order to get the energy to operate the capture and storage system.

Conclusions

Anthropogenic emissions of CO_2 to the atmosphere are large and growing. Humans have become a very important and very complex component of the global carbon cycle. Through use of fossil fuels and manipulation of the Earth's surface humans are significantly perturbing the natural cycling of carbon on a global scale. Increasing globalization of the economy and increasing linkage of human activities results in increasing complexity of the human component, and increasing difficulty in isolating my carbon from your carbon.

Acknowledgements

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TABLES

Fuel	Emissions coefficient (kg C/10^9 J net heating value)
Lignite	27.6
Anthracite	26.8
Bituminous coal	25.8
Crude oil	20.0
Residual fuel oil	21.1
Diesel oil	20.2
Jet kerosene	19.5
Gasoline	18.9
Natural gas	15.3

Table 1: A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned (from IPCC, 1997).

Country	1990	1998	2002
United States	0.19	0.17	0.15
Canada	0.18	0.18	0.16
Mexico	0.13	0.12	0.11
Global Total	0.17	0.15	0.14

Table 2: Emissions of CO_2 from fossil-fuel consumption (cement manufacture and gas flaring are not included) per unit of GDP for the United States, Canada, Mexico and for the global total. CO_2 is measured in kg C and GDP is in 2000 US$ purchasing power parity (from IEA, 2005).

Sector	United States	Canada	Mexico
Energy extraction and conversion[a]	46.2	36.2	47.7
Transportation[b]	31.3	27.7	30.3
Industry[c]	11.2	16.8	13.6
Buildings[d]	11.3	19.3	8.4

Table 3: Percent of CO_2 emissions by sector for 2003.

(a) the sum of three IEA categories, “public electricity and heat production”, “unallocated autoproducers”, and “other energy industries”,

(b) IEA category “transport”,

(c) IEA category “manufacturing industries and construction”,

(d) IEA category “other sectors”

(from IEA, 2005)

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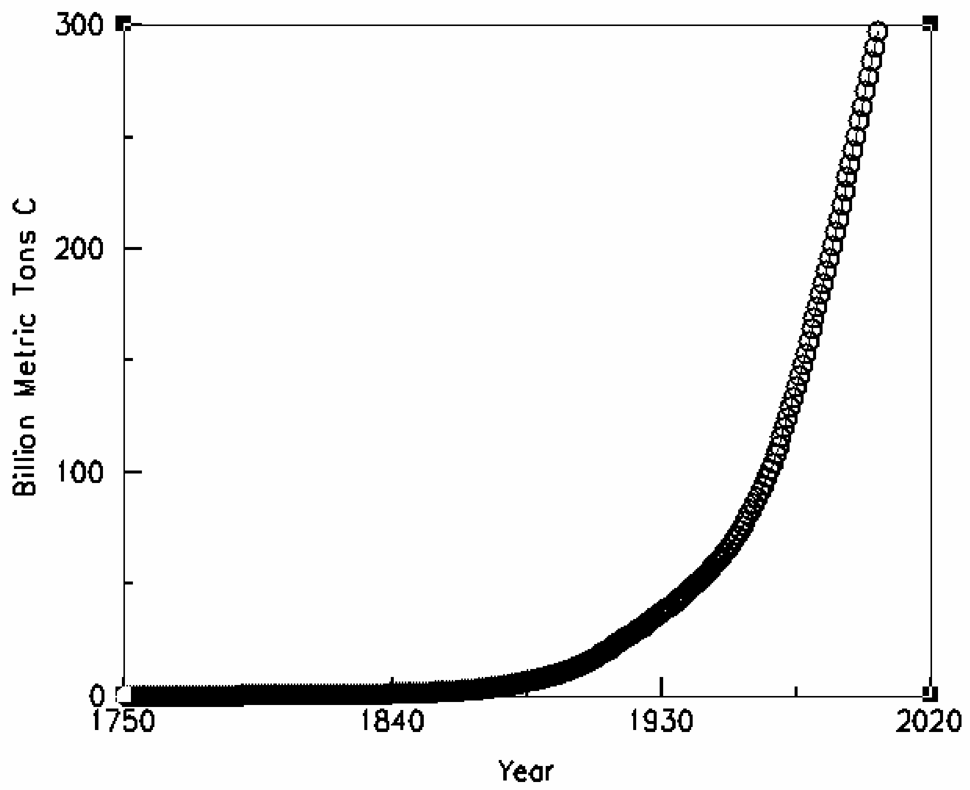

Figure 1: Cumulative global emissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002 (data from Marland et al., 2006).

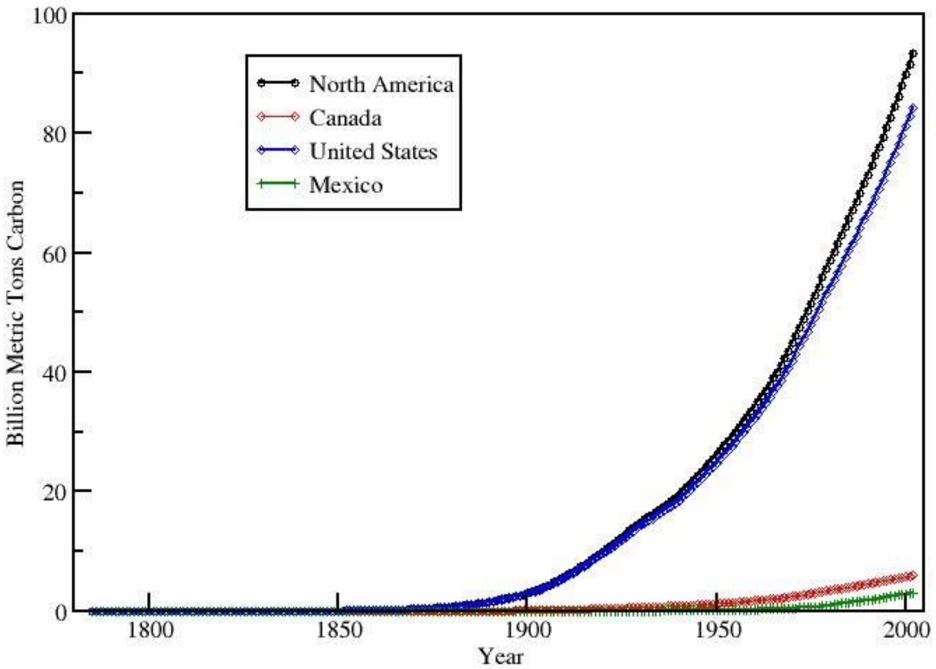

Figure 2: The cumulative total of CO_2 emissions from fossil-fuel consumption and cement manufacture, as a function of time, for the three countries of North America; and for the sum of the three (from Marland et al., 2006).

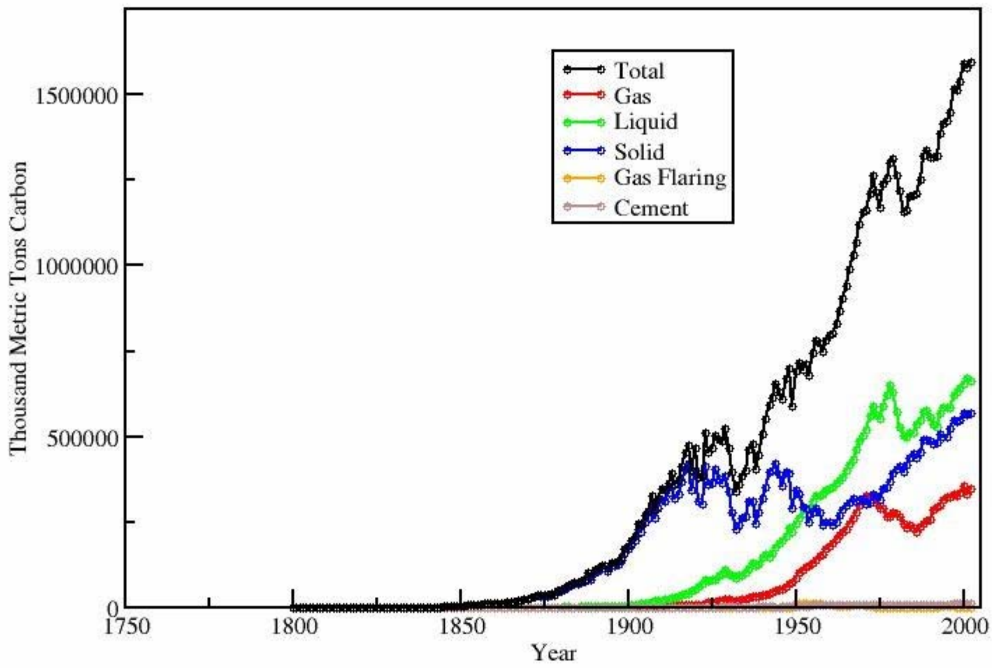

Figure 3: Annual emissions of CO_2 from fossil-fuel use, by fuel type, for the United States (from Marland et al., 2006). Gas, liquid, and solid refer to natural gas, petroleum products, and coal respectively. Small contributions from the flaring of natural gases at oil fields and from the manufacture of cement are included.

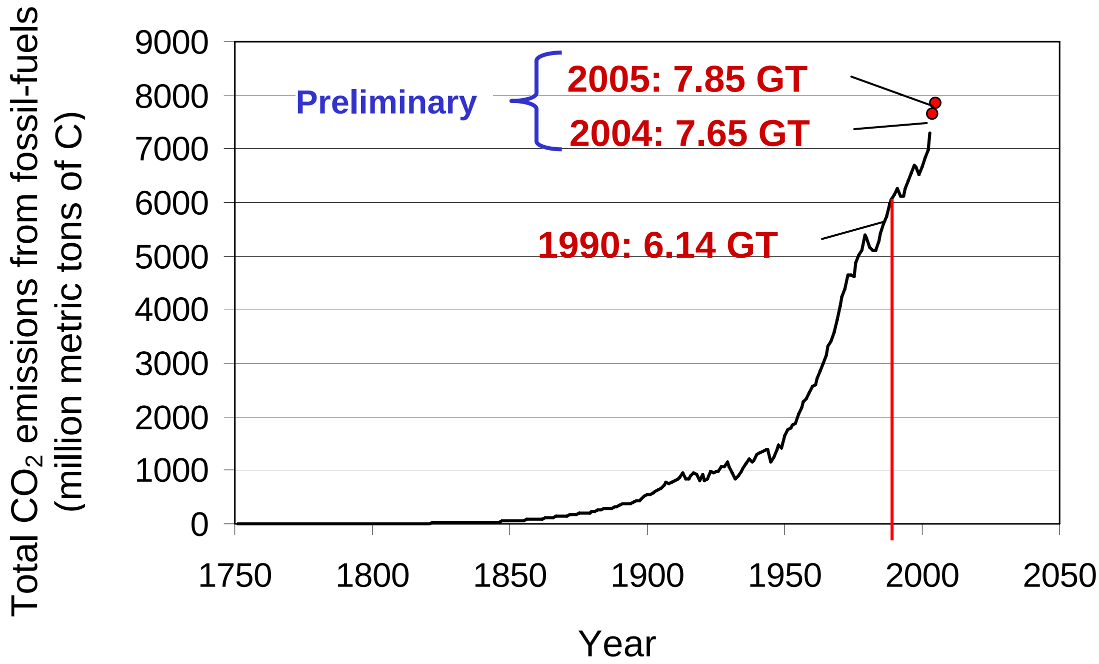

Figure 4: Total global emissions of CO2 from use of fossil fuels and manufacture of cement, 1751-2005. The values through 2003 are based on energy statistics from the United Nations for the period 1950 to 2003 and on energy statistics from a variety of sources for the period prior to 1950 (from Marland et al., 2006). Values for 2004 and 2005 are preliminary estimates derived by using energy statistics from the BP company to extrapolate from the earlier time series. The numerical value for 1990 is provided for reference. 6.14 GT C = 6140 million metric tons C.

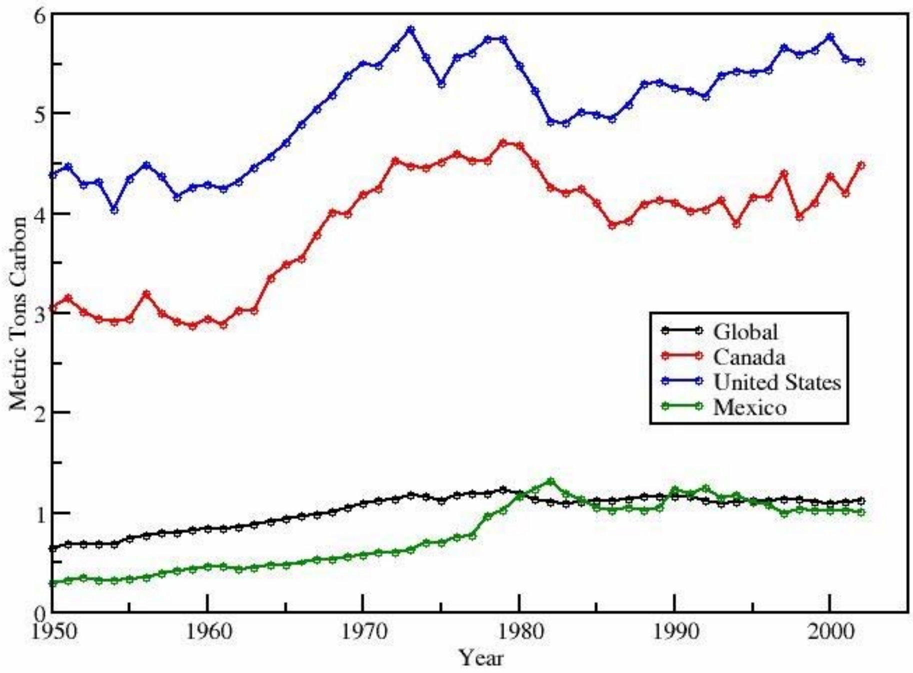

Figure 5: Per capita emissions of CO_2 (in metric tons of C per person per year) from fossil-fuel consumption (and cement manufacture) in the United States, Canada, Mexico, and for the global total of emissions (from Marland et al., 2005).

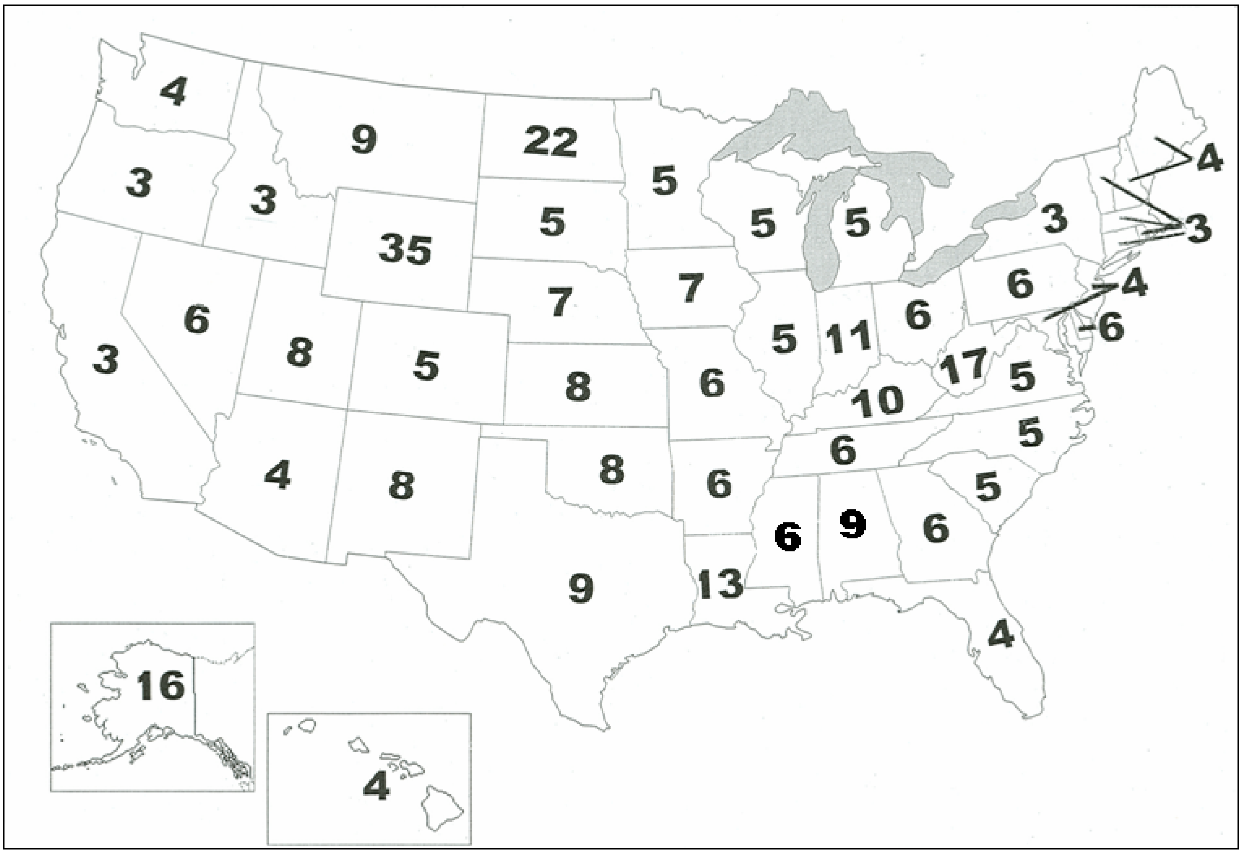

Figure 6: Per capita emissions of CO_2 from fossil-fuel consumption for the 50 U.S. states in 2000. To demonstrate the range, values have been rounded to whole numbers of metric tons C per capita per year (from Blasing et al., 2005b).

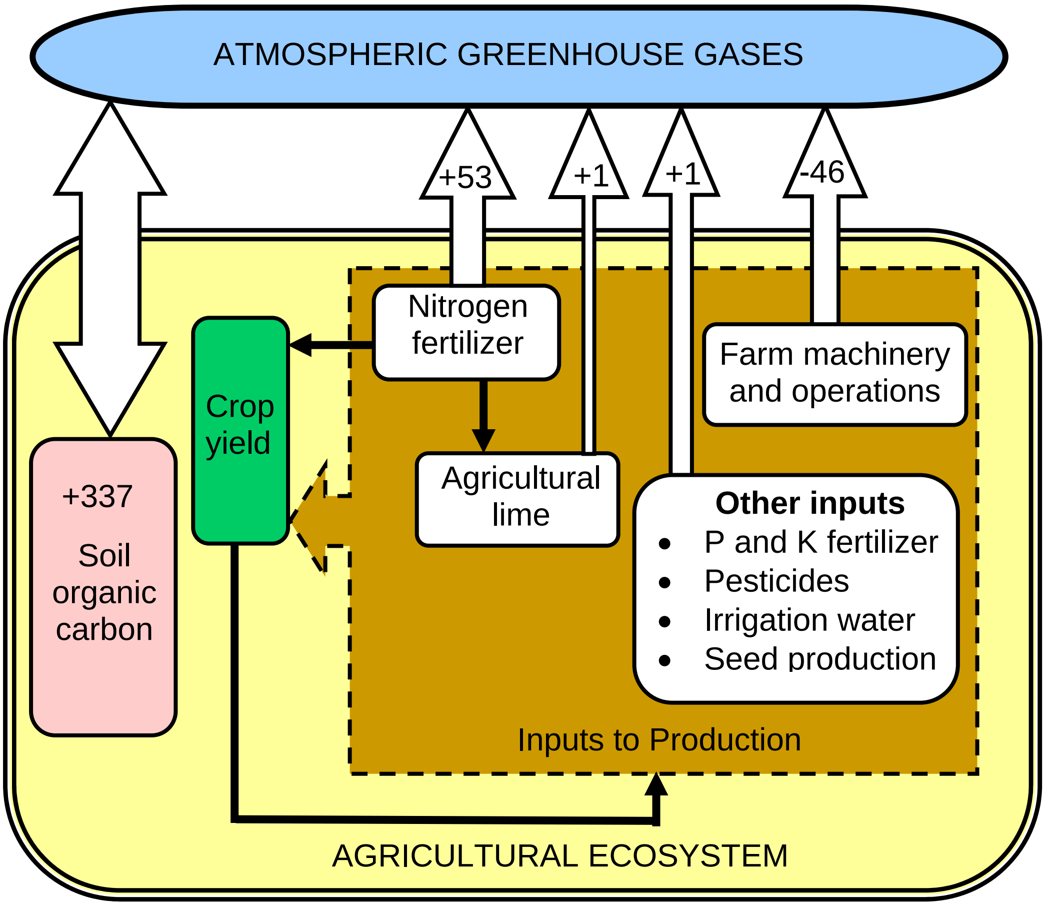

Figure 7: The net effect on greenhouse gas emissions for a change from conventional tillage to no-till agriculture. Data are based on average practice for all crops in the United States, circa 1995. Data are in kg C per hectare per year. The figure shows that while the organic C content of the soil is increased by 337 kg C per hectare per year, there is also a savings in emissions from fuel for farm machinery but an increase in emissions of the greenhouse gas nitrous oxide. Other inputs also change on average, and for any given location there may be a change in crop yield (from West and Marland, 2002).